JSSEIS

Journal of Sustainable Software Engineering and Information Systems

Volume 2, Issue 2, 113-125.
e_ISSN: 3123-3007
https://e-journal.gomit.id/jsseis
DOI: 10.58723/jsseis.v2i2.237

Digital Decision-Support Information Systems for Sustainable Crop Residue Management in the Indo-Gangetic Plains: An Evidence-Based Framework

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Article Info
Article history:
Received: August 20, 2026
Revised: October 25, 2026
Accepted: November 02, 2026

Keywords:
Agricultural Sustainability
Crop residue Management
Decision-Support Systems
Digital Agriculture
Indo-Gangetic Plains

Abstract

Background: Crop residue burning remains a major sustainability challenge in the rice-wheat system of the Indo-Gangetic Plains, while proven in-situ crop residue management (CRM) technologies still face adoption barriers.

Aims: This study develops an evidence-based digital decision-support information-system framework that translates known economic, institutional and environmental determinants of CRM adoption into functional system requirements.

Methods: A structured secondary synthesis was undertaken using the empirical evidence and cited literature contained in Sheoran et al. (2026). Evidence on farmer characteristics, information exposure, extension contact, machinery access, profitability, yield and greenhouse-gas outcomes was mapped to proposed digital modules.

Result: The framework integrates farmer and field profiles, machinery and Custom Hiring Center access, extension advisories, adoption-risk analytics, environmental surveillance, and outcome dashboards. It is grounded in evidence that CRM adoption is associated with higher wheat yield and net income, lower CO2 emissions, and stronger probabilities of adoption among farmers with education, social-institution membership, mass-media exposure, extension participation, machinery ownership and perceived conservation benefits.

Conclusion: Digital information systems can complement physical CRM technologies by reducing information and coordination frictions, targeting services and enabling transparent monitoring of economic and environmental outcomes. The framework requires field validation before operational deployment.

To cite this article: Ravish, P. (2026). Digital Decision-Support Information Systems for Sustainable Crop Residue Management in the Indo-Gangetic Plains: An Evidence-Based Framework. Journal of Sustainable Software Engineering and Information Systems, 2(2), 113-125. https://doi.org/10.58723/jsseis.v2i2.237
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INTRODUCTION

The rice-wheat cropping system is central to food production and rural livelihoods in the Indo-Gangetic Plains (IGP) of India. Its expansion has contributed substantially to national food security, yet the intensification of production has also created concerns related to soil degradation, water use, biodiversity, input dependence and environmental quality (Brainerd & Menon, 2014; Gathala et al., 2013; Rahman, 2015). Rice-wheat cultivation is particularly prominent across Punjab, Haryana and Uttar Pradesh, where a short interval between rice harvesting and wheat sowing creates a strong operational incentive to clear residues rapidly. Under mechanized harvesting, large quantities of anchored and loose paddy straw remain in the field, and open-field burning has consequently become an expedient residue-disposal practice (P. Kumar et al., 2015; S. Kumar et al., 2019).

The environmental and socioeconomic costs of this practice are substantial. The evidence reviewed by Sheoran et al. (2026) indicates that crop residue burning contributes to air pollution, soil-fertility loss and respiratory-health risks, while also generating avoidable nutrient and ecosystem-service

losses. Burning is attractive to farmers because it is fast and relatively low in labour requirements, but its external costs are transferred to the wider environment and society. For this reason, sustainable crop residue management (CRM) has increasingly become both an agricultural-technology issue and an information, coordination and policy problem.

In-situ CRM technologies provide a practical alternative to burning. Happy Seeder, Super Seeder and zero-till drill technologies enable wheat establishment with reduced or eliminated residue burning, while retaining residue in or on the soil. These approaches can improve resource-use efficiency and reduce production costs, and they have been associated with improvements in crop productivity, soil health and greenhouse-gas performance (Gathala et al., 2011; Jat et al., 2013; Shyamsundar et al., 2019). However, technical effectiveness alone does not guarantee adoption. The effective use of CRM machinery requires timely access, knowledge of suitable practices, awareness of benefits, extension support and institutional coordination during a very short post-rice-harvest window.

Research on CRM adoption shows that farm-level decisions are shaped by intertwined social, economic, institutional and technical determinants. Education, farm characteristics, extension contact, mass-media exposure and risk orientation have been identified as relevant predictors of sustainable agricultural technology adoption (Kaur et al., 2023; Keil et al., 2021; Priya & Singh, 2024; D. Singh & Kaur, 2019). Social networks also matter because farmers do not evaluate technologies in isolation; participation in institutions and interaction with peers can influence information access and perceived legitimacy of new practices. Extension services are therefore important not only for communicating technical instructions but also for reducing uncertainty and connecting farmers with the institutions that deliver machinery, schemes and advisory support (Takahashi et al., 2020).

Evidence from the focal empirical study provides a strong basis for translating these determinants into information-system requirements. Sheoran et al. (2026) analysed a survey of 900 farm households across Punjab, Haryana and Uttar Pradesh and used propensity-score matching (PSM), supported by inverse probability weighting (IPW), to assess economic outcomes. The study reported that CRM adoption was associated with positive effects on wheat yield and net income and with lower carbon dioxide emissions relative to conventional practice. The study also found statistically significant positive associations between CRM adoption and years of schooling, membership of social institutions, mass-media exposure, extension contact, extension participation, machinery ownership and perceived benefits of conservation agriculture.

The role of machinery access is especially important. CRM operations are time sensitive, and many farmers rely on cooperative societies, Custom Hiring Centers (CHCs) or nearby machinery owners for equipment services (Bhatt et al., 2023; Ghanghas et al., 2024; Härri et al., 2020; Omotayo et al., 2025). Even when a technology is agronomically suitable and profitable, a farmer may still burn residue if equipment is not available at the required time. Similarly, a farmer who lacks accurate information about machinery, subsidies, local service providers, crop establishment practices or expected benefits faces higher search and coordination costs (Balakrishnan et al., 2021; Olusanya et al., 2026; Ugwu et al., 2025). These constraints suggest that an intervention focused only on the physical supply of machines may underperform when the associated information infrastructure is weak.

The existing evidence establishes the economic and environmental value of CRM and identifies major determinants of adoption, but it does not by itself provide an integrated digital mechanism for acting on those determinants (Abourokbah et al., 2026). In practice, information relevant to CRM may be fragmented among farmers, extension agencies, machinery owners, CHCs, local institutions and policy administrators. A digital information system can potentially connect these actors by consolidating farmer needs, equipment availability, advisory content, intervention eligibility, environmental monitoring and program outcomes in a common decision-support structure (Jones et al., 2026; Mouratiadou et al., 2023).

This opportunity is consistent with the policy implications advanced in the focal study. Sheoran et al. (2026) call for stronger CHC models, awareness and sensitization, incentives, institutionalization of CRM, better policy integration and the use of surveillance technologies such as drones and remote sensing to identify CRM adoption at micro level. These recommendations imply a need for software and information-system capabilities that can acquire, integrate, analyse and communicate data. The

present paper therefore reframes sustainable CRM not only as a machinery-adoption problem but also as a sustainable information-systems problem.

The purpose of this paper is to develop an evidence-based digital decision-support framework for sustainable crop residue management in the Indo-Gangetic Plains. The specific objectives are: (1) to synthesize the adoption, economic and environmental evidence reported in the focal CRM study; (2) to translate empirically observed adoption determinants into functional information-system requirements; (3) to propose an integrated architecture linking farmers, machinery services, extension support, environmental surveillance and outcome monitoring; and (4) to identify implementation and validation priorities for future digital CRM research. The paper does not re-estimate the original econometric models and does not claim new causal effects. Its contribution is the systematic conversion of published agricultural evidence into a design framework suitable for sustainable software and information-system development.

METHOD

Research Design

A structured secondary evidence-synthesis and conceptual system-design approach was used. The primary evidence base was the empirical article by Sheoran et al. (2026), which examined the economic and environmental outcomes of CRM adoption in the IGP. Only evidence, concepts and references available within the uploaded focal article were used to develop the present manuscript. No external literature, unpublished dataset or additional web source was introduced (Pitsyk et al., 2026; Wyckhuys et al., 2025). This restriction was adopted to maintain a transparent evidence trail between the agricultural findings and the proposed information-system framework.

The focal study itself employed a purposive and multistage random sampling design covering nine districts in Punjab, Haryana and Uttar Pradesh. Three villages were selected within each sampled block, and adopters and non-adopters were interviewed using a structured questionnaire. The resulting sample comprised 900 households, with 600 adopters and 300 non-adopters at the survey stage. The original authors used PSM to address observable selection bias and IPW as a robustness procedure. Greenhouse-gas effects were synthesised from on-farm evidence and compared statistically between CRM and conventional practices (Sheoran et al., 2026).

Evidence Extraction and System-Requirement Mapping

Evidence was extracted into five analytical categories: farmer and household characteristics; information and institutional exposure; access to machinery and services; economic outcomes; and environmental outcomes. Each category was then mapped to a corresponding digital function. For example, the positive association between extension participation and CRM adoption was mapped to an advisory and extension-engagement module; the strong association with machinery ownership was mapped to a machinery inventory and CHC scheduling module; and the reported reduction in carbon emissions was mapped to an environmental-performance monitoring module. The mapping process was interpretive rather than statistical and was used to derive a coherent decision-support architecture.

The proposed system follows a closed-loop logic. Input data describe the farmer, field, crop calendar, residue load, access conditions and current CRM practice. Service-access data describe machinery, CHC availability, institutional participation and extension contact. An analytics layer combines these variables to identify information gaps, service bottlenecks and priority cases. A decision-support layer generates actionable outputs for farmers, extension personnel and administrators. Finally, environmental and economic outcomes are recorded and returned to the system as feedback for future planning.

Analysis Plan and Scope

The analysis used descriptive synthesis, evidence-to-requirement mapping and conceptual architecture development. Numerical results from the focal study are reported only as published and are not presented as newly generated findings. Because the design is conceptual, no software prototype, usability experiment, cybersecurity assessment or field deployment was undertaken.

Accordingly, the framework should be interpreted as a testable design specification rather than a validated operational system. Future research should implement a prototype and evaluate its performance with longitudinal farmer, machinery, environmental and program-delivery data.

RESULTS AND DISCUSSION

Result:

Evidence Base for Digital CRM Decision Support

The focal evidence demonstrates that sustainable CRM delivers outcomes that are sufficiently measurable to support digital monitoring. In the PSM estimates, overall CRM adoption increased wheat yield by 251 kg ha−1 and net income by INR 2,070 ha−1 relative to matched non-adopters. Technology-specific estimates were stronger: Happy Seeder adoption was associated with a 376 kg ha−1 yield increase and an INR 15,045 ha−1 income increase; Super Seeder with 308 kg ha−1 and INR 8,844 ha−1; and zero-till drill with 335 kg ha−1 and INR 16,386 ha−1. IPW estimates were directionally consistent, supporting the robustness of the economic results (Sheoran et al., 2026).

Environmental performance also provides a clear monitoring target. CRM practices were associated with mean CO2 emissions of 649.7 kg ha−1 compared with 699.8 kg ha−1 under conventional practice, a statistically significant difference of −50.1 kg ha−1. The wider literature cited in the focal paper links sustainable residue management with lower fuel, fertilizer, irrigation and energy requirements and with improved soil and resource-use performance (Chethan et al., 2020; Fagodiya et al., 2023; P. Singh et al., 2021; R. Singh et al., 2022). These outcomes indicate that a digital CRM platform should not measure adoption as a simple yes/no event. It should also capture yield, income, energy-related indicators and environmental benefits so that program performance can be evaluated against multiple sustainability objectives.

Table 1. Evidence from the focal CRM study and its digital relevance

Evidence dimension	Published evidence	Digital implication
Study coverage	900 households across Punjab, Haryana and Uttar Pradesh; adopters and non-adopters compared using PSM and IPW.	Platform should support multi-location farmer, field and intervention records with comparable outcome indicators.
Information exposure	Mass-media exposure, extension contact and extension participation were positively associated with CRM adoption.	Provide targeted advisories, extension messaging, engagement history and alerts.
Institutional/social factors	Membership of social institutions had a strong positive association with adoption.	Include institutional affiliation and local-network channels for communication and service delivery.
Machinery access	Ownership of machinery had the largest reported marginal effect among listed adoption variables.	Maintain live machinery/CHC inventory, booking, service radius and availability status.
Economic outcomes	CRM adoption was associated with higher wheat yield and net income; technology-specific effects differed.	Track technology-specific yield, cost and income outcomes to support evidence-based recommendations.
Environmental outcomes	CRM practices reduced CO2 emissions relative to conventional practice.	Integrate environmental indicators and remote-sensing/drone evidence into sustainability dashboards.

Adoption Determinants as Information-System Requirements

The strongest design insight is that CRM adoption depends on more than farm size or age. In the focal probit model, years of schooling had a positive marginal effect, while membership of social institutions increased the probability of sustainable residue management by approximately 23%.

Mass-media exposure was associated with a 17.7% higher probability, extension contact with 13.8%, extension participation with 24.2%, machinery ownership with 32.8%, and perceived benefits of conservation agriculture with 17.6% (Sheoran et al., 2026). These results provide a direct rationale for a platform that identifies information, service and perception gaps rather than treating all non-adopters as a homogeneous group.

A farmer-support module could therefore maintain a minimal profile containing location, crop calendar, preferred language, technology history, access to machinery, extension contact and institutional affiliation. The purpose of such profiling would not be to exclude farmers from support but to identify which enabling service is most relevant (Masi et al., 2022; Mizik, 2022; Molina-Maturano et al., 2022). A farmer with limited machinery access may require equipment scheduling; a farmer with low awareness may require a tailored advisory; a farmer already connected to extension services may need only operational reminders. In this way, the same empirical variables used to explain adoption can become inputs for service personalization (Daum et al., 2021; Rajkhowa & Qaim, 2021; Rose et al., 2016).

The design should also recognize that informational variables can be proxies for wider institutional capacity. Education may improve a farmer's ability to interpret technical information, while social-institution membership may increase access to trusted advice and collective services. Mass media and extension channels may accelerate diffusion of knowledge from research institutions to farmers (Barmon et al., 2026; Härri et al., 2020; Nguyen-Anh et al., 2022; Raza et al., 2019; Roy et al., 2018). The digital system should therefore strengthen, not replace, these human networks. It should provide extension personnel and local institutions with better targeting, scheduling and follow-up tools.

Proposed Digital Information-System Architecture

Figure 1 presents the proposed architecture. The first component is an input-data layer containing farmer profile, field characteristics, cropping schedule, residue-management status and previously used CRM technology. A second access layer records machinery availability, CHC services, extension channels, scheme eligibility and institutional participation. These two data streams enter an analytics layer that identifies adoption barriers, estimates service priority and tracks pending actions. The decision-support layer then presents different outputs to farmers, service providers and administrators.

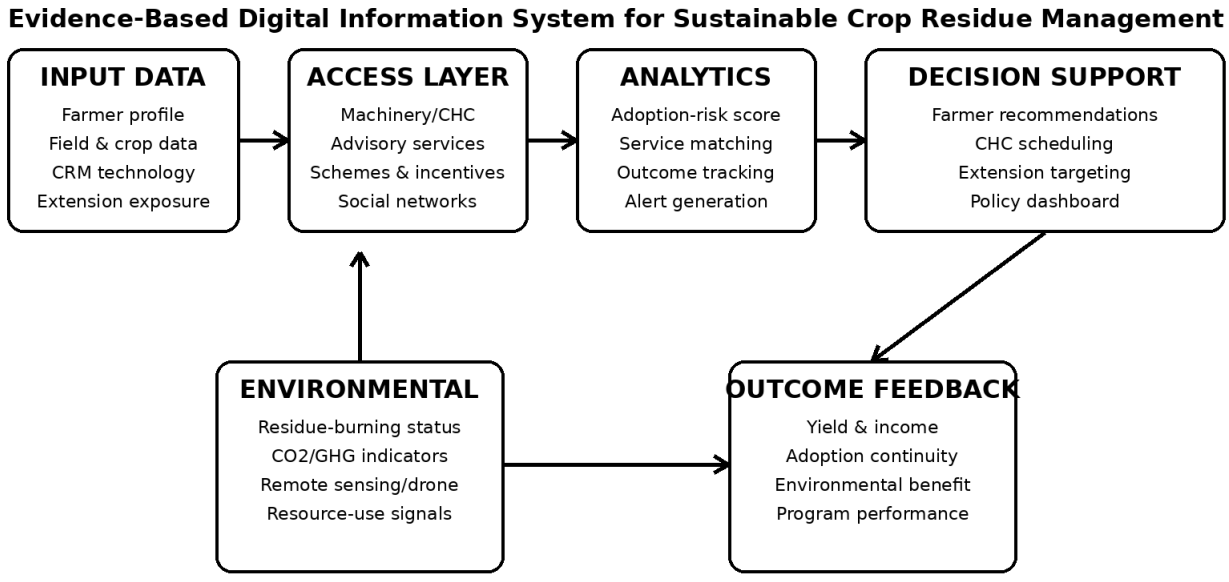


Figure 1. Proposed evidence-based digital decision-support architecture for sustainable crop residue management.

For farmers, the interface could display recommended residue-management options, operational windows, available machines, nearby CHC services and extension advisories. For machinery providers, the system could aggregate local demand and support booking or routing decisions. For

extension agencies, it could identify clusters of farmers requiring awareness, technical guidance or follow-up. For administrators, a dashboard could summarize adoption, machinery utilization, program reach, yield and income outcomes, and environmental indicators. The architecture therefore converts fragmented activities into a connected information flow.

A central feature is the environmental layer. The focal study recommends advanced surveillance tools such as drones and remote sensing for micro-level identification of CRM adoption. In a digital platform, these observations could be linked with farmer and field records to support verification and spatial targeting. The system could also maintain technology-specific sustainability indicators, including CO2-related estimates, fuel or energy proxies, and residue-retention status. This would support transparent reporting of environmental benefits while creating a longitudinal evidence base that is absent from cross-sectional adoption studies.

Functional Modules and Sustainability Logic

Table 2. Functional modules proposed for the digital CRM information system

Module	Core data	Primary function	Sustainability value
Farmer and field registry	Location, crop calendar, residue status, prior CRM use	Create a reusable farm-level information profile	Reduces repeated data collection and enables targeted support
Machinery and CHC module	Machine type, ownership, availability, booking window	Match demand with Happy Seeder, Super Seeder or zero-till services	Reduces access and timing constraints that can trigger burning
Extension and media module	Advisory content, extension contact, participation history	Deliver timely technical and awareness messages	Strengthens information access and perceived benefits
Adoption-support analytics	Education, institutional links, service access, prior adoption	Flag service gaps and prioritize extension follow-up	Focuses resources on modifiable adoption barriers
Environmental monitoring	CRM status, CO2/GHG indicators, remote-sensing/drone observations	Verify practice and monitor environmental performance	Connects adoption with measurable environmental outcomes
Outcome dashboard	Yield, income, utilization, reach, environmental indicators	Compare interventions over time and across locations	Supports evidence-based policy, incentives and accountability

The sustainability logic of the platform is based on complementarity between software and physical technology. CRM machinery directly changes field operations, whereas the information system changes the conditions under which machinery is discovered, accessed, scheduled and evaluated. This distinction is important. A digital application cannot substitute for adequate machinery supply or effective extension institutions, but it can reduce search costs, reveal service bottlenecks and improve coordination. In this sense, the software layer supports the efficient use of existing physical and institutional resources.

The architecture also creates a basis for economic feedback. Because the focal evidence shows that yield and income responses differ across CRM technologies, outcome records can help avoid a one-size-fits-all recommendation strategy. Historical local performance could be presented alongside agronomic guidance to improve farmer understanding of expected benefits. Such feedback may strengthen perceived usefulness, which itself was positively associated with sustainable residue-management behaviour in the focal study. However, recommendations should be transparent and should clearly distinguish observed historical associations from guaranteed future outcomes.

Implementation Pathway

Implementation should begin with a limited pilot rather than immediate large-scale deployment. A district-level pilot could first establish a registry of participating farmers, CHCs and available CRM machines. The platform would then test three high-value functions: time-bound machinery matching, targeted extension communication and recording of CRM outcomes. The short operational interval between paddy harvesting and wheat sowing makes scheduling performance a critical system metric. Useful pilot indicators would include booking success, waiting time, completed CRM operations, extension response, continued adoption, yield and income reporting, and completeness of environmental records.

Institutional integration is equally important. The focal evidence emphasizes the role of extension agencies, social institutions and CHCs. Therefore, a technically sophisticated platform that operates outside these institutions may have limited effect. The system should instead provide role-specific access: farmers receive services and advisories; CHCs manage equipment availability; extension staff monitor engagement and unresolved cases; and administrators view aggregated program indicators. Data collection should be minimized to variables that support a clear service or evaluation purpose so that the system does not become an administrative burden.

Incentive design can also be supported digitally. Sheoran et al. (2026) recommend push-and-pull policy mechanisms, repurposed subsidies, stronger CHC business models and potential carbon-market incentives for environmental benefits. A digital platform could provide traceable records of verified CRM operations and associated performance indicators, creating the information infrastructure needed for transparent incentive administration. Nevertheless, any payment or carbon-credit mechanism would require independent methodological validation; the present framework does not propose that the reported mean CO2 difference be automatically converted into tradable credits.

Proposed Evaluation Metrics for a Future Prototype

A future prototype should be evaluated against both information-system performance and agricultural sustainability outcomes. The first group of indicators should measure whether the platform improves access and coordination. Examples include the proportion of registered farmers receiving an advisory before the residue-management window, the share of machinery requests successfully matched to a CHC or service provider, average waiting time between request and operation, and the percentage of priority cases receiving extension follow-up. These indicators are directly connected to the institutional and machinery-access factors associated with adoption in the focal study (Sheoran et al., 2026).

The second group should measure actual CRM behaviour. Registration or app use is not equivalent to sustainable management; therefore, the central operational outcome should be the proportion of participating fields in which residue is managed through the intended CRM practice rather than burning. Technology-specific completion rates for Happy Seeder, Super Seeder and zero-till drill should be recorded because the focal evidence shows different economic responses across technologies. Where feasible, field records could be complemented by remote-sensing or drone observations, consistent with the surveillance approach proposed by Sheoran et al. (2026).

The third group should capture economic and environmental performance. Yield and net income should be recorded in comparable units so that digital recommendations can be evaluated against farmer welfare rather than adoption counts alone. Environmental monitoring should include a consistent indicator of CO2 or broader greenhouse-gas performance, while recognizing that the focal estimate of a 50.1 kg ha−1 reduction is a study result rather than a universal conversion factor. Additional resource-use variables, such as irrigation, fuel and fertilizer use, could be incorporated because the literature synthesized in the focal article links CRM with lower energy and input requirements (Chethan et al., 2020; Fagodiya et al., 2023; P. Singh et al., 2021).

Finally, the evaluation should include continuity and equity. Continued CRM use in subsequent seasons would indicate whether digital support contributes to durable behaviour rather than one-time compliance. Participation rates should also be examined across different farmer profiles and access conditions so that the platform does not inadvertently advantage farmers who already possess stronger institutional links or machinery resources. The objective of adoption-support analytics

should be to identify where support is needed, not to ration assistance according to predicted adoption probability. These measures would allow a future field trial to test whether the proposed information system creates additional value beyond existing mechanization and extension arrangements.

Table 3. Suggested indicators for field evaluation of a digital CRM prototype

Evaluation domain	Illustrative indicator	Interpretation
Access and coordination	Successful machinery matches; waiting time; advisory reach	Whether software reduces information and service bottlenecks
Adoption behaviour	Verified non-burning CRM operations by technology	Whether digital support translates into field-level practice
Economic outcome	Wheat yield and net income per hectare	Whether adoption remains economically attractive to farmers
Environmental outcome	CO2/GHG indicator and resource-use proxies	Whether operational adoption is associated with measurable environmental benefit
Continuity	Repeat CRM use in subsequent seasons	Whether the intervention supports durable adoption
Equity	Participation and service completion across farmer groups	Whether benefits reach farmers with different access conditions

Implications:

For sustainable software engineering, the framework illustrates that environmental value should be defined in terms of the real-world process improved by the software. The proposed system is sustainable not merely because it is digital, but because it is intended to reduce avoidable burning, improve utilization of CRM machinery, strengthen extension reach and support measurement of economic and environmental outcomes. Evaluation should therefore include both conventional system measures, such as reliability and usability, and domain sustainability measures, such as completed non-burning operations, machinery utilization and verified environmental performance.

Research Contribution:

The principal contribution of this paper is a domain bridge between sustainable agriculture and sustainable information systems. Existing CRM research demonstrates that technology choice, information exposure, institutional contact, machinery access and environmental outcomes are interdependent. The proposed framework converts these relationships into software functions and data flows. It thereby shifts the digital-agriculture discussion from generic monitoring toward an evidence-based decision-support design that targets specific adoption frictions documented in the IGP.

Limitations:

The framework has several limitations. First, it is derived from a secondary synthesis centered on one cross-sectional empirical study and the references contained within that article. The focal study itself notes that cross-sectional data cannot capture long-term soil-health and sustainability effects and that PSM and IPW control for observed covariates but not all unobserved determinants of adoption (Sheoran et al., 2026). Second, the present paper does not develop or test a working software prototype. Consequently, no claims can be made regarding usability, system performance, cybersecurity, cost-effectiveness or causal impact on adoption.

Suggestions:

Future studies should develop a prototype and evaluate it prospectively across multiple agricultural seasons. Longitudinal data would allow researchers to examine whether digital support improves continued CRM adoption, machinery utilization, yield stability, income and environmental outcomes over time. System studies should also compare different levels of digital intervention for example,

information-only support versus integrated machinery scheduling and extension follow-up to identify which functions generate the greatest practical value. Finally, remote sensing or drone-based verification should be tested against field observations before it is used for compliance or incentive decisions.

CONCLUSION

Sustainable crop residue management in the Indo-Gangetic Plains is simultaneously a technological, environmental, economic and information-coordination challenge. Evidence from the focal CRM study shows that Happy Seeder, Super Seeder and zero-till drill technologies can improve wheat productivity and farm income while lowering carbon emissions compared with conventional residue-burning practice. The same evidence also shows that adoption is strongly connected to information exposure, extension participation, institutional membership, machinery access and perceived benefits. These factors are precisely the kinds of variables that a well-designed information system can organize and act upon.

This paper therefore proposes an evidence-based digital decision-support framework integrating farmer and field records, machinery and CHC access, extension communication, adoption-support analytics, environmental surveillance and outcome dashboards. The framework does not replace machinery, extension or policy institutions; rather, it provides a software layer that can connect them and make their services more timely, targeted and measurable. By linking economic and environmental outcomes to operational decision support, the approach offers a clear sustainability rationale for information-system development in agricultural residue management.

The next research step is empirical validation. A functional prototype should be piloted with farmers, CHCs and extension agencies and evaluated over multiple crop seasons. Such work would determine whether the proposed system actually reduces coordination barriers, expands non-burning residue management, improves service delivery and produces reliable sustainability data. If validated, an integrated digital CRM platform could complement existing policy and mechanization initiatives and contribute to more resilient, lower-emission rice-wheat production systems in northern India.

ACKNOWLEDGMENT

Not applicable.

AUTHOR CONTRIBUTION STATEMENT

PR: Conceptualization, methodology, evidence synthesis, framework development, visualization, writing - original draft, and writing - review and editing.

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